A Review of Risks in the Solar Electric Life-Cycle

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Abstract

Early studies of risks in the life cycle of solar electric technologies do not represent their current stage of development. Our study updates the data used in previous studies and also accounts for the full life-cycle of photovoltaics. We show that the non-radiological risks of the solar electric- and nuclear-life cycles are approximately equal. This contradicts the conclusions of some earlier studies according to which the former presented much greater occupational and public non-radiological risks than the latter.

1. Introduction

The generation of energy is associated with environmental- and health-risks as materials and fuels are extracted, processed, used, potentially abused, and decommissioned. The mix of energy supply mix and related infrastructure in each country determines the likelihood of routine and potential accidental releases of contaminants that can affect public heath and the environment. The environmental impacts of each energy source differ greatly and include the following: a) local pollution related to extracting fuels, and to the construction materials; (b) local or regional atmospheric pollution from the combustion of fossil fuels (e.g., urban smog, acid rain); (c) global climate change due to the emission of greenhouse gases (GHGs) generated by producing, transporting, and using fossil fuels; (d) land use for a range of energy-related activities; and (e) risks attributed to various fuel-chain cycles (fires, explosions, spills, radioactive emissions, nuclear weapon proliferation).

In this paper, we reviewed the early studies of risks in the solar electric fuel cycle and updated them, using current data on materials use and occupational illnesses.

2. Review of Previous Studies

Previous risk assessments of fuel cycles focused on occupational- and public- health effects, ecological damages, and social and economic damages (Inhaber, 1979; 1982; Holdren, 1980). However, studies of the external costs of non-conventional energy sources, such as photovoltaics (PV), need to be often updated because current technologies are rapidly evolving and new technologies enter the market place. Inhaber (1979) compiled the occupational- and public-risks associated with the following stages of conventional and renewable sources of electricity: materials production, plant construction and operation, maintenance, and transportation. He concluded that the risks associated with renewable energy technologies were greater than those from some conventional forms of power generation. For example, his estimates of occupational risk suggested that the photovoltaic fuel-cycle was 15 times riskier than the nuclear-fuel cycle, while his public-risk estimates represented the former as being 333 times riskier than the latter. According to Inhaber (1979), wind-, solar thermal-, and solar electric-generation, all had approximately the same occupational and public risks, and their occupational risks were even larger than those of coal-based electricity production. However, several reviews revealed that Inhaber's study was flawed by multiple errors stemming from inconsistent assumptions and conceptual misunderstandings (Holdren et al., 1980). Holdren et al. rebuffed Inhaber's conclusions based on data from the US Bureau of Labor Statistics along with workforce requirement data from the Bechtel Energy Supply Planning Model (Carasso et al., 1975). Holdren's study showed that renewable energy sources, such as wind and solar electric, are equal to, or better than, conventional coal electricity in terms of occupational effects. Inhaber corrected some of his assumptions in a 1982 publication but his overall conclusions remained the same. For example, he showed 3-6 and 10-200 times higher occupational and public days lost, respectively, for the PV fuel-cycle than for the nuclear fuel-cycle. Inhaber later (1987) reiterated his argument that the solar- and wind-fuel cycles are riskier than the nuclear cycle because of their high materials usage and their requirements for back-up energy.

In the last decade, the risks of electricity were determined as a part of estimating the external costs of electricity. Two studies, the External Costs and Benefits of Fuel Cycles by the Oak Ridge National Laboratory (ORNL, 1995), and the European ExternE study (ExternE, 1999), are among the most detailed ones. However, they did not discuss the risks associated with solar energy. Thus, the only published life-cycle risk assessment studies pertaining to solar technologies are those previous ones by Inhaber and Holdren. Considering the rapid evolution of PV module technologies and Balance of System (BOS) configurations, their conclusions are far from the current reality. For instance, the conceptual PV plant configuration described in Inhaber's study corresponded to a 30-year-old Jet Propulsion Laboratory (JPL) prototype that required 20 times more aluminum than a current PV plant configuration (JPL, 1976; Inhaber, 1979; Mason et al., 2005). In the absence of other data, other authors have cited the estimated risks based on the 1976 prototype in more recent works (e.g., Bezdek, 1993).

Besides the issue of the representativeness of the data, the methods used in those early studies did not account for the full life cycle of PV. For example, although both Inhaber's and Holdren's studies investigated risks associated with materials production, the upstream risks associated with electricity and fuel usage were not taken into account.

3. Methodology

Our study departs from these earlier studies in two ways. First, we use up-to-date data on PV module and balance of system (BOS) materials composition. Second, we compiled the occupational risks linked to the entire life cycle materials and energy use, in particular, investigating those risks associated with fuel and electricity use that were omitted from the early studies. We used the latest injury data from the Bureau of Labor Statistics, minerals and materials production data from the US Geological Survey (USGS), gas- and fuel-production data from the Energy Information Administration

(EIA), and other material-specific production data from industry statistics. In agreement with the Holdren, and ExternE studies, but in contrast to Inhaber's assessment, we did not include a back-up system for PV. This omission represents the reality of the market for PV that is almost entirely based on grid-connected installations without separate back-up systems.

3.1 Occupational Risks

The complete life cycles of PV and nuclear electricity are divided into sub stages: materials production, plant construction, operation, and the end of life. The upstream risks as well as onsite risks for each stage were determined. Radiological occupational risks were not included since those risks are difficult to quantify due to the long-term effects of such exposures. Fatal injuries were not investigated mainly because, for most industries, their numbers are insufficient for deriving a statistically reasonable conclusion. The reference PV system used in our study is a 3.5 MW system in Springerville, Arizona, comprising multi-crystalline silicon photovoltaic modules; we used actual performance data for this installation and also extrapolated its performance to average U.S. solar-irradiation data (i.e., 1800 kWh/m^2/yr). For the nuclear-fuel cycle, we selected for modeling risk, a standard 1000-MW pressurized water reactor (PWR) which is representative of many nuclear power plants in the United States and in Europe.

3.2 Life Cycle Inventory Analysis

The first step for compiling the life-cycle occupational risks for PV- and the nuclear-fuel cycle was to take inventory of materials usage and energy consumption during the life cycle of the systems being compared, using published data. Table 1 shows the aggregated material requirements assumed in the early studies, and those in current PV systems; there is a striking difference between the current and old estimates for the usage of aluminum and steel.

Table 1: PV Material Requirements Used for Calculating Risks (metric ton / MWp)

Study	*Steel*	*Aluminum*	*Concrete*	*Glass*	*Silicon*	*Total*
Inhaber, 1979	Not available					9900*
Inhaber, 1982	135	410	45	20	20	630
Holdren et al., 1980	0-180	0-200[a]	20-2500	10-70	N/A	30-2950
Mason et al., 2005	40	19	76	85[b]	13[c]	235

* Inhaber quotes a total of 330 MT/MW-yr; we assumed that he used a 30-yr life expectancy
[a] Estimated from nonferrous materials requirements of 280 MT/MWp.
[b] From Meijer et al., 2003
[c] Including process loss of 40-70% of loss, depending on production method (Alsema, 2003; Jungbluth, 2005). Assume 12% electrical conversion efficiency.

Table 2 presents the materials- and energy-usage of PV life cycle based on multicrystal silicon modules (Alsema, 2003; Meijer et al, 2003), and the BOS of the Springerville PV power plant. Mason et al (2005) give details of the PV BOS configuration.

Table 2: Life cycle materials- and energy-usage for typical mc-Si modules and BOS

Life Cycle	*Materials and Energy*	*Mass (kg/ MW_p)*
Module Materials	Charcoal	10500
	Coke	18000
	EVA	11000
	Glass	101000
	HCl	20000
	Naphtha	7000
	PC	6900
	PVC	3500
	PVF	3200
	Quartz sand	76000
	Shaft coal	18000
	NaOH	7300
	Steel, galvanized	2900
	Wood	39000
BOS Components for 1 MWp mc-Si	Steel	40000
	Aluminum	19000
	Copper	7500
	Plastics	5800
	Concrete	76400
	Water	61000
Energy[a]	Fuel (GJ)[b]	6500
	Electricity (GJ)	10000

[a] The energy use includes consumption during the materials production.
[b] The fuel is assumed to be100% natural gas

Likewise, the materials and energy use during the US nuclear fuel cycle was investigated mainly from the literature and government statistics (Table 3). The construction-related risks were determined only for building the nuclear power plant. Lack of data precluded us from including the risks associated with the construction of other nuclear facilities (e.g., fuel enrichment facilities). For assessing energy use, the electricity requirement during uranium enrichment was considered, assuming that 50% of the uranium for the reactor is enriched by the gaseous diffusion method and the other 50% by the gas centrifuge method, representing the current average situation globally.

Table 3: Approximate Materials requirement for a nominal 1000 MW PWR and Electricity usage for uranium enrichment (BHP research, 1999)

Materials and Energy	*Materials to construct a Power Plant (metric ton)*
Steel	51800
Concrete	652800
Copper	2700
Aluminum	90

Electricity for Uranium Enrichment (TJ/yr)	420

3.3 Occupational Risks from Materials and Energy Production

The numbers of nonfatal injuries and illnesses per kg of material were determined using data from government and industry statistics. The annual nonfatal injury and illness data were extracted from the statistics of the Bureau of Labor Statistics, Department of Labor (Table 4, column B). The numbers of "total recordable cases," were used, which combines "cases with days away from work," "cases with job transfer or restriction," and "other recordable cases," (DOL, 2005). Information on annual material production (Table 4, column A) was obtained mainly from statistics of the US Geological Survey (USGS); other sources included the Manufacturing, Mining, and Construction Statistics of US Census Bureau, Industry Statistics from the American Plastics Council, and the Annual Energy Review of the EIA.

To determine the risks associated with materials, the estimated risk (non-fatal injuries per 1000 tons) of each process is multiplied by a factor according to the mass balance and process flow available from a commercial LCA database (Althaus et al, 2003). For example, 0.4 kg of coal and 1.5 kg of iron ore (with 65% Fe) are consumed to produce 1 kg of steel product. The risks associated with energy production also are computed by a similar rule by combining nonfatal injury and illness data and energy production data. We did not consider the use of recycled materials in our modeling. Uncertainties exist in modeling complicated industry processes so that some minor materials may not be taken into account. They can be reduced if the input-output economic table is applied to the injury data so that the risks of the entire industry supply chains are fully considered (Holdren et al., 1980). However, that application is reserved for a future task to supplement the current analysis.

Table 4: Breakdown of non-fatal occupational injuries and illnesses for material processing

Material	*Process*	*SIC/NAICS Code*	*A:Annual Production (1000 metric tons)*	*B:Non-fatal injuries per year*	*B/A: Non-fatal Injuries per 1000 metric tons (per MJ)*
Steel	Iron mining	101	51800	300	0.0058
	Coal mining	12	990000	5480	0.0056
	Blast furnace and basic steel products	331	93900	18800	0.15
Aluminum	Bauxite mining[a]	109	N/A	N/A	0.016
	Primary Aluminum manufacturing	3334	2930	2030	0.69
Concrete	Sand & gravel mining	144	1150000	1370	0.0012
	Crushed and broken limestone mining and quarrying	212312[b]	984000	1400	0.0014
	Lime manufacturing	3274	19100	5100	0.27
	Ready-mix concrete	3273	78000	11400	0.15
Copper	Copper ore	102	1260	200	0.16
	Copper smelting and refining	3331	1480	200	0.13

	Copper wire drawing	331422[b]	1880	1200	0.73
Glass	Potash, soda, and borate mineral mining	1474	14200	200	0.014
	Crushed and broken limestone mining and quarrying	1422	994000	1400	0.0014
	Sand & gravel mining	144	1150000	1370	0.0012
	Flat glass	321	4840	1670	0.39
Plastics	Petrochemical manufacturing	2865/2869	81300	3200	0.073
	Plastics material and resin manufacturing	2821	44900	2200	0.049
	Plastics product manufacturing	3261[b]	44900[c]	23100	0.35
Other Materials	Alkalis and Chlorine	2812	31000	300	0.01
	Wood, Lumber	241	35500	4750	0.13
	Water, except Irrigation	494	3.78E+08	2500	6.6E-06
Energy	Crude petroleum and natural gas (MJ)	131	3.37E+13	2330	6.9E-11
	Petroleum Refineries (MJ)	291	3.87E+13	1330	2.6E-11

* SIC: Standard Industry Classification;
NAICS: North American Industry Classification System

[a] Since bauxite is no longer mined in the United States , we combined the man hour requirement (0.5 man hour/ton of ore) data and the injury rate per 100 workers from the BLS statistics to determine the injury factor (Holdren et al., 1980; Inhaber, 1982)

[b] NAICS

[c] The amount of plastic product is assumed to be the same as the amount of resin produced.

Table 5 shows the risks determined by those steps. The injury and illness factors from a study of electricity risk were adapted to represent the current US electricity fuel-mix (Inhaber, 1987).

Table 5: Estimates of non-fatal occupational injuries and illnesses per unit amount of materials and energy.

Material and energy	*Non-fatal injuries (per 1000 metric tons)*
Steel	0.19
Aluminum	0.75
Glass	0.0045
Copper	1.06
Plastics	0.47
Concrete	0.15
Water	6.6E-06
Fuel (Natural gas)	6.9E-08 (per GJ)
Electricity[a]	4.6E-03 (per GWh)

[a] Adapted from Inhaber, 1987.

3.4 Occupational Risks from On-site Labor

The nonfatal injuries and illnesses associated with stages other than materials and energy usages are measured from man-hour requirements and incident rates at each stage. In our analysis, these stages include manufacturing PV modules, constructing PV- and nuclear-power plants, and operating them.

The labor requirements for manufacturing the PV module and for constructing the PV plant were obtained directly from industry sources. Since separate nonfatal injury and illness statistics on incident rate during PV module manufacturing are unavailable, we used as a surrogate those data in NAICS 334413 (SIC 3674), "Semiconductor and related device manufacturing," which includes the PV industry. Similarly, the injury and illness rates of NAICS 2362 (SIC 154) "Nonresidential building construction" were used for the PV plant's construction.

The occupational risks of injuries and illness for the mining/milling, nuclear plant operation, and decommission of nuclear power plant were obtained directly from a Oak Ridge National Laboratory report (ORNL, 1995). The occupational risks from disposing of spent nuclear fuels were taken from the Environmental Impact Statement of the Yucca Mountain project (US-DOE, 2002). For constructing the nuclear reactor, the incident rate in NAICS 2371, "Utility System Construction" was used; this was multiplied by 22 million man-hours of workforce required for building a reactor, according to Energy-Economic Data Bases (EEDB, 1987). Again, lack of data prevented us from including other stages like uranium enrichment, conversion, PV decommissioning, and recycling of materials.

3.5 Estimates of Public Risks

According to Inhaber (1982) the public-health risks are proportional to the emissions of SO_2, which, in turn, are proportional to the amounts of steel and aluminum used in the life-cycle of photovoltaics.

Table 6 lists the early calculations of risk and those we obtained with the same methodology using up-to-date material requirements. The risks from producing and transporting materials decrease dramatically when recalculated with the current PV configuration. Without relying on a back-up system, which is the case for the majority of the PV market, our up-to-the-minute estimates show that the occupational and public risks from the current PV fuel cycle are approximately equal to those in the nuclear fuel cycle. Moreover, a significant fraction of solar modules sold these days do not have aluminum frames; this further reduces these risks (Figure 1).

Table 6: Risks of PV and Nuclear Fuel Cycles: Old and Current Estimates (lost-work-days per MW-yr)[e.]

Fuel Cycle		Materials Acquisition & Construction	Emissions from Materials Production	Operation & Maintenance	Energy Back-up	Energy Storage	Transportation	Total
PV	**Early Estimates**							
	Occupational, Canada, (Inhaber, 1979)		Details not available					150
	Occupational, Canada, (Inhaber, 1982)	7.6-13	-	7.4	2.-3.3	3.3-5.9	2.1-6.5	22.5-36
	Occupational, US, (Holdren, 1980)		Details not available					1.3-2.8
	Public, Canada, (Inhaber, 1979)		Details not available					500
	Public, Canada, (Inhaber, 1982)	-	28-87	-	15-43.8	-	1-2.3	44-133
	Our Estimates[a]							
	Occupational, Canada	3.2-5.0	-	2.3[d]	-	-	0.3-1.0	5.9-8.4
	Occupational, Southwestern US[c]	1.9-3.0	-	1.4[d]	-	-	0.2-0.6	3.5-5
	Public, Canada	-	1.1-3.3	-	-	-	0.16-0.4	1.3-3.7
	Public, Southwestern US[c]	-	0.7-2.0	-	-	-	0.1-0.24	0.75-2.2
Nuclear[b]								
	Occupational, Canada, (Inhaber, 1982)							4.1-10.9
	Public, Canada, (Inhaber, 1982)							0.6-3.6
	Occupational, US, (Holdren, 1980)							0.14-0.44

[a] The calculated risks are based on the PV plant's configuration (Mason, et al, 2005) and the framework of Inhaber's 1982 study .

[b] The life-cycle stages of the nuclear-fuel cycle differ from those of the PV fuel cycle; a detailed breakdown is not shown here.

[c] Solar radiation in southwestern US is assumed to be 1.67 times that of Canada. Inhaber(1982) also made this assumption.

[d] The man-hours for operation and maintenance in Inhaber's study (1 man-hour/MWh) was updated based on current practice (0.3 man-hour/MWh). Cleaning solar panels, considered an important portion of maintenance in Inhaber's study, is unnecessary in modern PV plants.

[e] 5.8-18 MDL are assigned for each metric ton of sulfur oxides based on an early study (Comar and Sagan, 1976). On the other hand, the Canadian emission factors of sulfur oxides from with steel and aluminum production were 10 and 49g/kg of metal, respectively, determined from the Canadian pollutant inventory of 1974 and the annual material production statistics (United Nations, 1977; Air Pollution Control Directorate, 1978). As a result, 0.058-0.18 (=0.01 x (5.8-18)) and 0.3-0.9 (=0.049 x (5.8-18)) MDL per ton of material are allocated for steel and aluminum, respectively. Then, an MDL of 27-87 due to the emissions from materials production can be deduced as follows: First, the materials requirements for steel and aluminum, 135 and 410 ton per MWp are converted to 540 and 1640 $MW_{average,}$ respectively, using a factor

of 4. Then, with a 30-year PV plant lifetime, 18 and 54.5 ton of steel and aluminum is required each MW-yr of electricity generation. Multiplying these materials requirement per MW-yr with those MDL estimates results in a range of 17-52 MDL[1]. By applying an adjusting factor of 1.67 for Canadian solar radiation , the range of 28-87 MDL is obtained.

[1] For steel, 18 x (0.058-0.18) = 1.1-3.3, for aluminum, 54.5 x (0.3-0.9) = 16-49. Therefore, the total range is 17-52.

4. Discussion

The non-fatal occupational injuries per MWh of electricity from the PV- and nuclear-fuel cycles are summarized in Tables 7 and 8, and in Figures 1 and 2. The inputs used in these calculations are as follows:

- The lifetime of the reference PV module and BOS is 30 years.
- The efficiency of the PV modules is 12.2%.
- The recorded annual electricity production of an 1 MWp PV power plant in Springfield, Arizona is 1688 MWh (reference case), and 1420 MWh for the average solar irradiation conditions in the United States.
- The capacity factor of the reference nuclear power plant is 90% (the net power is 900 MW), the fuel burn-up is 45 MWd/t of U, and it generates 7100 GWh of electricity in a year.
- The lifetime of the reference nuclear power plant is 40 years.

Our results show (Figure 2) that the highest risks of occupation injuries in the PV fuel cycle are associated with Module Manufacturing, while the Power Plant Construction is the most risky stage of the nuclear fuel cycle. The distribution of risks across the life cycle stages differ from the life-cycle emissions and energy profiles. For example, nuclear-fuel enrichment, the stage with the most greenhouse-gas emissions in the nuclear-fuel cycle, is not significant in terms of occupational risks. Also, unlike the energy consumption profile wherein module manufacturing accounts for only 7% of the total primary energy usage, our analysis shows that this stage poses the greatest occupational risks. Overall, the nuclear- fuel cycle shows approximately the same incident rate as the PV fuel-cycle. This finding drastically contrasts with the cited early studies. Inhaber's revised study (1982) and the Holdren et al. study (1980) presented the PV life-cycle as being 3 to 10 times riskier than the nuclear fuel life-cycle in terms of occupational injuries (Table 6). Our results suggest that the progress made during the last two decades in the efficiency of PV modules along with BOS configuration has greatly reduced the occupational risks of PV-generated electricity.

Table 7: Non-fatal occupational injuries and illness during the PV life cycle

Life Cycle		*Injuries per TWh*	*%*
Module Materials	Charcoal	0.001	0.0
	Coke	0.002	0.0
	EVA	0.107	1.9
	Glass	0.009	0.2
	HCl	0.004	0.1
	Naphtha	0.001	0.0
	PC	0.065	1.1
	PVC	0.032	0.6
	PVF	0.030	0.5
	Quartz sand	0.002	0.0

	Shaft coal	0.002	0.0
	NaOH	0.001	0.0
	Steel, galvanized	0.013	0.2
	Wood	0.104	1.8
	Fuel (GJ)	0.009	0.2
	Energy input, electricity (GJ)	0.252	4.4
Module Manufacturing		1.919	33.3
BOS Components for 1 MWp mc-Si	Steel	0.182	3.2
	Aluminum	1.068	18.6
	Copper	0.158	2.7
	Plastics	0.055	0.9
	Concrete	0.275	4.8
	Water	0.000	0.0
BOS construction		1.050	18.2
Plant Operation		0.415	7.2
Total		5.76	100.0

Table 8: Non-fatal, non radiological occupational injuries and illness during the nuclear-fuel life cycle

	Life Cycle	Injuries per TWh	%
Uranium mining		0.316	6.4
Uranium milling		0.280	5.7
Electricity for Enrichment		0.118	2.4
Materials for Power Plant			
	Steel	0.043	0.9
	Concrete	0.34	6.8
	Copper	0.01	0.2
	Aluminum	0.001	0.0
	Materials Total	0.39	7.9
Plant construction		2.67	54
Plant Operation		1.09	22.0
Plant decommissioning		0.014	0.3
Spent fuel disposal		0.05	1.0
Transportation		0.008	0.2
Total		4.96	100.0

5. Conclusion

We investigated the life-cycle occupational risks for the PV- and nuclear-fuel cycles on the basis of three data elements: annual non-fatal injuries and illnesses in the United States, annual materials production in the United States, and the workforce required for a life-cycle stage. The injuries and illnesses associated with each stage, including fuel- and materials-production, power-plant construction, and electricity generation were complied. The results show that both have about the same level of risk as determined for non-fatal occupational injuries and public health risks from sulfur dioxide emissions upstream of electricity production. However, the greatest risks of the nuclear-fuel cycle are those due to radiological effects and catastrophic events that were not examined in this study.

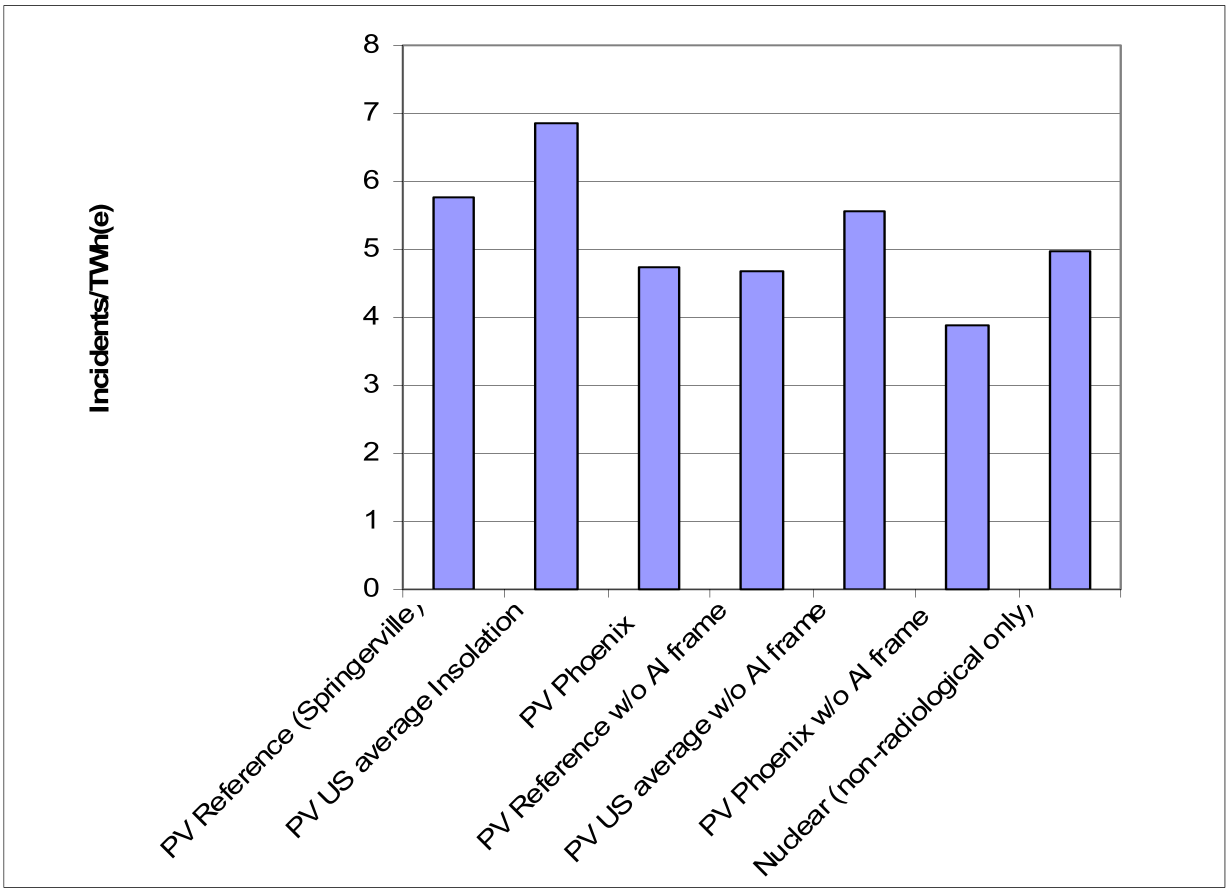

Figure 1:Non-fatal, non-radiological injuries and illness during the PV- and nuclear-fuel cycles.

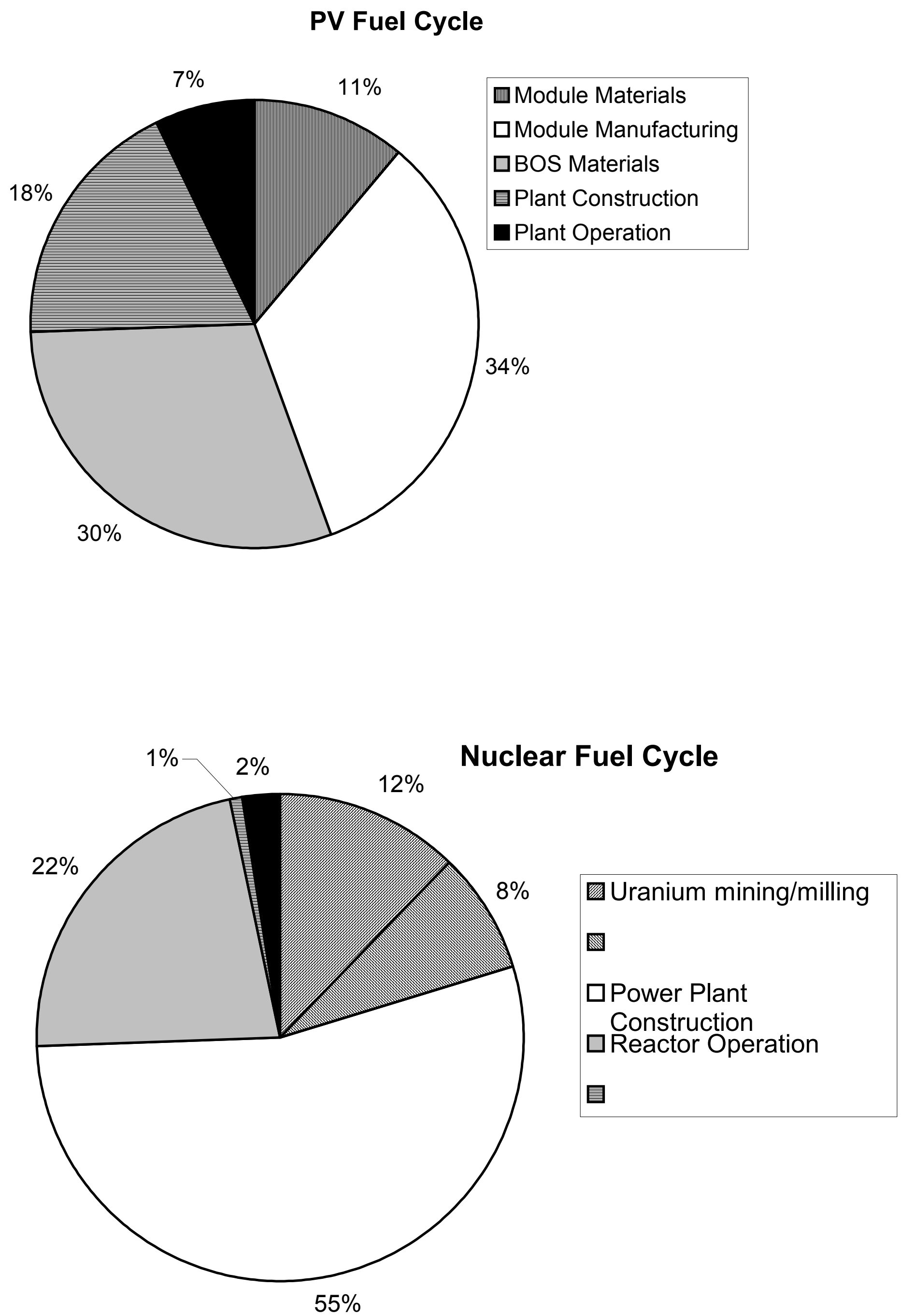

Figure 2: Breakdown of Non-fatal, Non-radiological Occupational Risks for the PV- and Nuclear-Fuel Cycles

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